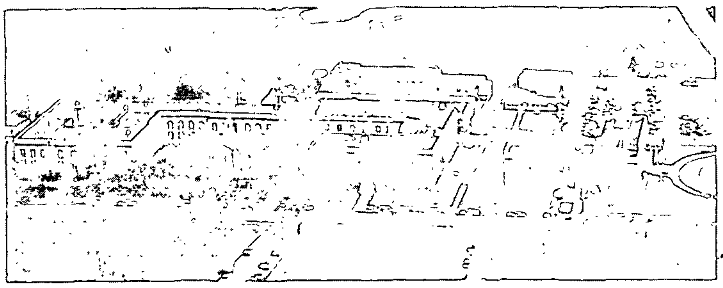

THE INSTITUTE OF PAPER CHEMISTRY, APPLETON, WISCONSIN

IPC TECHNICAL PAPER SERIES
NUMBER 40

EFFECTS OF TENSION WOOD ON KRAFT PAPER FROM A SHORT-ROTATION HARDWOOD (*POPULUS* "*Tristis* #1")

R. A. PARHAM, K. W. ROBINSON AND J. G. ISEBRANDS

SEPTEMBER, 1976

Effects of Tension Wood on Kraft Paper
From a Short-Rotation Hardwood
(*Populus* "*Tristis* #1")*

By

R. A. Parham
K. W. Robinson
The Institute of Paper Chemistry
Appleton, Wisconsin

J. G. Isebrands
USDA Forest Service
Institute of Forest Genetics
Rhinelander, Wisconsin

*The experimental phase of this investigation was carried out by K. W. Robinson in partial fulfillment of the requirements of The Institute of Paper Chemistry for the M.S. degree from Lawrence University, Appleton, Wisconsin.

Abstract

The physical properties and morphology of kraft paper handsheets obtained from tension wood of intensively managed, 5-year-old trees of *Populus* "*Tristis* #1" were compared to those produced from isolated normal wood of the same stems. Pulp yields of tension wood (TW) and normal wood (NW) were 60 and 53%, respectively. Over a beating range of 0-45 minutes, strength properties of TW paper were in all cases noticeably inferior to those obtained from NW. During paper formation, the TW or gelatinous fibers resisted collapse, even upon extended refining, and produced thick, porous sheets of poorly bonded elements. It was concluded that the differential behavior of NW and TW pulps was in several respects analogous to those displayed by earlywood and latewood pulps, respectively, of softwood species as well as thin- *vs.* thick-walled hardwood fibers. Consequently, it appears that the inferior strength of TW paper is primarily a function of fiber morphology, and the difference in hemicellulose content between NW and TW (viz., lower pentosan content of TW) often cited in the literature as a potential major factor here probably contributes little if any significant effect on ultimate interfiber bonding and paper quality.

This paper has been submitted for publication in *Wood Science and Technology*.

Introduction

One of the major challenges for the pulp and paper industry over the next quarter century will be to procure an adequate supply of suitable wood fiber (Keays 1975). At present, it appears that a promising, supplementary source of fiber will be whole-tree chips of rapidly grown, short-rotation hardwoods subjected to intensive management (Ribe 1974). Utilization of such material may be necessary in order to accommodate future market demands for hardwood pulp in general. The latter will be essential in high quality papers (Schroeder 1976) to perpetuate already established levels of bulk, opacity, softness, absorbency, reduced porosity, and good surface texture. Furthermore, the demonstrated rapid growth and coppicing ability of certain species when cultivated on lands marginally suited for conventional agriculture (Dawson and Hutchinson 1972) demand that short-rotation, intensive management be considered as part of a potential solution to the anticipated fiber crunch.

Whole-tree chips of the above hardwoods will consist primarily of juvenile wood and contain elevated levels of bark as well as reaction wood (Einspahr 1976), and such factors will have an effect on their suitability for pulp and paper. However, there is some evidence that trees in the range of 6-20 years old will yield paper of generally acceptable quality, with the possible exception of reduced tear strength; also, if residual bark is kept to about 5%, pulp yields as well as chemical requirements may remain close to those characteristic of more mature trees (Einspahr 1976).

One anatomical feature of rapidly grown, juvenile hardwoods which has received only minimal consideration to date is the potential quantity of reaction wood or tension wood (TW) present in such trees. This oversight is perhaps understandable, because TW produces high chemical-pulp yields and is commonly thought to be associated with leaning stems and branches rather than vertical stems. However, this disregard is suprising in view of the following facts: (1) TW has been shown to exert generally adverse effects on paper properties, especially those that rely on interfiber bonding (Jayme and coworkers 1951; Watson 1956; Dadswell et al. 1958), and (2) TW has been found to occur in large quantities in vertical stems of some hardwoods, especially *Populus* (Kaeiser 1955; Isebrands and Bensend 1972), and has been associated with rapid growth (Berlyn 1961; Correns 1961; White and Robards 1965; Isebrands and Bensend 1972; Krempl 1975). Moreover, large percentages of TW have been found in young *Populus* grown under intensive culture (Isebrands and Parham 1974; Anderson and Zsuffa 1975).

Although the properties of TW have been well reviewed (Hughes 1965; Timell 1969; Côté et al. 1969; Scurfield 1973), more information is needed on the specific effects of TW on paper quality, and particularly for the TW obtained from short-rotation hardwoods. As previously mentioned, some studies have shown a generally detrimental influence of TW from large and leaning trees. However, other investigations have produced rather inconsistent or even contradictory findings (e.g., Clermont and Bender 1958; Klauditz 1962), perhaps as a consequence of: (1) the failure or inability to adequately define the fraction of TW pulp in test papers, or (2) confounding variables such as species and/or pulping process. Consequently, in view of the above circumstances, the present work was initiated to evaluate the quality of paper produced from normal and tension wood pulps of young, rapidly growing *Populus*. In addition, we wanted to learn which difference in these pulps, i.e., chemical or morphological, is the most significant factor in determining resultant paper properties.

Experimental

Materials

The trees employed for this study were erect, 5-yr-old stems of the clone *Populus* "*Tristis* #1" (Cram 1960) growing under intensive management (see Crist and Dawson 1975). The first 90-cm stem segment above ground level was harvested and cut, while fresh, into 2-cm-thick disks with a sharp bandsaw. Identification of tension wood (TW) and normal wood (NW or non-TW) zones was then made after the cross-sectional disks were dried for 3-4 min in a microwave oven; regions composed of TW became silvery in color and shrank noticeably along the grain. Examination of microtome sections of such regions confirmed that they consisted largely of TW. Both TW and obviously non-TW zones were chiseled from the disks and reduced to approximately the same chip size before air drying in preparation for pulping.

Pulping

A kraft cook simulating recommended commercial conditions was carried out in a six-unit microdigester according to previously established procedures (Thode *et al*. 1961, Gardner and Einspahr 1964). All pulps were washed in deionized water, and three digester units each of NW and TW pulp were then separately combined. Kappa numbers determined by TAPPI T 236 m-60 were between 10 and 11, corresponding to residual lignin contents of about 1.5%. Pulp yields for TW and NW were 60 and 53%, respectively, an expected trend (Jayme and coworkers 1951; Watson 1956). Wood and pulp sugars were determined in duplicate by gas chromatography (Borchardt and Piper 1970).

Pulp and Paper Testing

Pulps were beaten for 15, 30, or 45 min in a Jokro mill using only two mill cups, which were rotated between duplicate 16-g charges of either TW or NW pulp. After they were refined, the pulps were dispersed in a British disintegrator and tested in triplicate via TAPPI T 227 m-58 for Canadian standard freeness.

From each beating interval, 10 handsheets (ca. 60 g/m^2 basis weight) were formed according to TAPPI T 205 m-58. Five handsheets of each pulp type were formed from unbeaten stock. The physical properties of these papers were then tested by TAPPI and other routine procedures in The Institute of Paper Chemistry's Paper Evaluation Laboratory. The resulting data were subjected to an analysis of variance for pulp type and beating time.

Microscopy

Standard microscope slides of unbeaten and beaten pulps were prepared for fiber length measurement (Ilvessalo-Pfaffli and Alfthan 1957) by TAPPI T 401 os-74. To ascertain the true composition of the pulps, we stained slides of unbeaten fibers with malachite green or C-stain and examined them under polarized light to see wall dislocations characteristic of TW fibers (Isebrands and Parham 1974). A count of 200 unbeaten fibers from each pulp type revealed that each consisted of about 95% pure NW or TW.

Wet pulp samples were critical-point-dried and prepared for scanning electron microscopy (SEM) (Parham 1975). Handsheet surfaces and some test failure zones were also examined via SEM, as well as cross sections of handsheet specimens exposed to a high humidity atmosphere and then cut with a scalpel under liquid nitrogen.

Results

Handsheet Morphology

Cross-sectional views of unbeaten NW and TW papers revealed a remarkable difference in sheet caliper. While the relatively thin-walled fibers of NW collapsed even unbeaten to form a well consolidated fiber mat (Fig. 1), TW pulp formed a very porous mat, with many fibers retaining an oval cross section (Fig. 2). The failure of TW fibers to readily deform during paper formation has in the past been attributed to the supposedly thick walls of "gelatinous" or "G"-fibers (Jayme and coworkers 1951; Watson 1956; Dadswell et al. 1958). However, Fig. 2 shows that TW fibers even with thin G-layers resisted collapse. Figure 2B also illustrates the brittle nature of a fractured G-layer as well as the surface dislocations characteristic of TW pulp fibers (see Isebrands and Parham 1974).

[Fig. 1-2 here]

We considerably reduced the difference in caliper of the NW and TW papers by refining the pulps for 45 min, but the TW handsheets still appeared noticeably more porous (Fig. 3).

[Fig. 3 here]

The paper structure inferred by cross-sectional analysis was substantiated by observations of the handsheet surfaces (Fig. 4-5). Failure zones in physical test specimens — for example, zero-span tensile — also implied better bonding within the NW paper (Fig. 6). Fibers tended to break more frequently in the latter handsheets, in contrast to prevalent fiber pull-out in the TW paper.

[Fig. 4-6 here]

Pulp and Paper Testing

Physical test data of NW and TW pulp and handsheets over a beating range of 45 min followed a trend that correlated logically with the morphology of papers depicted in the SEM micrographs. Figure 7 shows that TW pulp required substantial refining to produce paper with the density and reduced porosity equivalent to even that of the unbeaten NW pulp. Beating reduced the average caliper of the TW paper by 23.0% compared to only 13.2% for NW. However, most of this thickness reduction occurred during the first 15 min of refining, after which the TW paper thickness stabilized and would not reduce under similar pressure to even that of the unbeaten NW stock (Fig. 7).

[Fig. 7 here]

As a function of beating time, all paper strengths indicated a consistent inferiority of TW pulp to that of NW (Fig. 7). When these same strength properties were graphed as a function of sheet density, TW still formed a thicker and more porous sheet, and never equaled that of even the unbeaten NW. The TW still produced lower values of fold endurance, burst, and tear, although valid comparisons were possible (i.e., in the same density range) only between the NW-0 and TW-45-min samples. If beaten for 15-45 min, the TW sheets did surpass unbeaten NW sheets of similar density in tensile, stretch, zero-span tensile, and tensile stiffness. However, after only 15 min of beating, the NW paper was consistently superior in strength to that achieved by TW paper over the entire range of refining or sheet density.

Between 0 and 45 min of beating, neither NW or TW pulp suffered a significant reduction in mean fiber length (inclusive of fragments $\geq$ 0.2 mm). Normal wood was reduced only from 0.65 to 0.63 mm, while TW pulp went from 0.68 to 0.66 mm. Note also that the unbeaten pulp fiber lengths of NW and TW were approximately the same.

Implications and Discussion

Reasons for the generally inferior strength of paper obtained from TW fibers can be gleaned from consideration of G-fiber ultrastructure. Firstly, the presence of a G-layer significantly limits the degree of collapse and subsequent interfiber bonding a pulp fiber can achieve during consolidation into a paper web, even after refining. Moreover, the results of this study indicate that thin as well as thick, bulky G-layers can be an impediment in this respect. Consequently, the rheological properties of this cellulosic, highly ordered, and limitedly hygroscopic layer of wall substance apparently influence significantly the ultimate behavior of entire TW fibers.

The particular manner in which TW and NW pulp freeness decreased with beating time (Fig. 8) produced further insight into the general character of TW pulp fibers. Increased fiber conformability during early refining and progressive effects of fibrillation, cutting, and fines accumulation upon extended beating are usually cited in explanation of a general decrease in freeness with refining. In addition, thicker walled fibers tend to be altered much more so than ones with thinner walls and concomitantly, usually exhibit a greater rate of freeness reduction (Watson and Dadswell 1962). Interestingly, although TW pulp was initially freer than NW pulp, it became less free after 30 min of beating. Therefore, the differential response of TW and NW to beating is quite informative, because it parallels very closely the relationships displayed, respectively, by thick-walled and thin-walled eucalypt fibers (Watson and Dadswell 1962), latewood *vs.* earlywood fibers of loblolly pine (Watson and Dadswell 1962), as well as TW *vs.* NW fibers of eucalypts (Dadswell *et al.* 1958).

[Fig. 8 here]

From SEM observations of critical-point dried pulps, we could not visually confirm an increased fibrillation of well beaten TW over that of similarly processed NW, and a pulp fractionation was not carried out to quantify fines content. However, the relationship between pulp freeness and sheet density (Fig. 9) revealed that, while freeness of NW pulp decreased continuously as sheet density increased to 30 min of beating, the collapse-resistant TW fibers reached essentially a constant sheet density after only 15 min, but freeness continued to drop. Evidently, then, factors other than fiber flexibility, such as extensive fibrillation and a greater fines fraction, were influential in controlling TW pulp drainage. If so, then the behavior of TW pulp freeness with beating time might well be analogous to the aforementioned trends for various types of thick-walled fibers.

[Fig. 9 here]

In past literature, a difference in chemical composition of NW and TW has been cited as one of the prime causes of reduced interfiber bonding in TW paper. Specifically, TW usually has a somewhat lower-than-normal content of pentosan or xylan (Dadswell et al. 1958). In fact, for reaction wood pulps in general, the consensus has apparently been that low-strength paper made from conifer compression wood is a consequence of fiber morphology, while that from TW is probably more related to wood or pulp chemistry (Dadswell et al. 1958).

As was expected, the xylan content of TW pulp in the present work was about 5% less than for NW pulp (13 vs. 18%, respectively). However, it has been reasoned by Timell (1969) that the lower xylan of TW is almost entirely a result of the incorporation of additional cellulose (via the G-layers) into the wood, and the decrease compared to NW is therefore only apparent; actually, each TW fiber contains the same or only slightly less xylan than a typical NW fiber. Furthermore, since the S1 layer of the TW fiber wall, and especially the S2, are much thinner in G-fibers, the concentration of xylan in these layers must actually be considerably higher than for NW fibers (Timell 1969). Consequently, TW fibers in reality probably contain an adequate reserve of pentosan to serve as an adhesive (Obermanns 1936) for interfiber bonding. Therefore, we believe that the morphology of TW fibers is more likely the governing factor in the behavior of resultant pulps, and any direct influence of a difference in hemicellulose chemistry would appear to be, at best, of minor significance.

Another feature of G-fiber ultrastructure that apparently remains to be clarified is the nature of the wall dislocations regularly spaced along the surface of G-fibers (see Fig. 2). In past studies employing light microscopy, these dislocations have been designated as slip planes and minute compression failures. Such zones are known to promote an increase in the percentage of broken fibers during acid-sulfite pulping and have an obvious deleterious effect on pulp strength (see Dadswell et al. 1958; Wardrop 1963). However, from our observations on TW pulp fibers, it would appear that some type of dislocation is restricted mainly to the surface of the G-fiber wall, specifically the S1 layer. Whether or not these surface irregularities seen via SEM can be considered equivalent to the obvious wall bucklings mentioned above, and whether or not they are a detriment to kraft paper quality, requires further study.

Conclusions

Tension wood from short-rotation *Populus* produces paper of consistently inferior strength properties in comparison to normal wood of the same tree. Moreover, we contend that the gelatinous fibers of tension wood (i.e., ones with a G-layer) of any hardwood species will have this same general effect.

Our results suggest that the morphology and ultrastructure of tension wood fibers are the major factors in governing behavior of these fibers in pulp form, and that the lower xylan content of tension wood in contrast to normal wood probably contributes little if any direct effect on ultimate paper quality.

Although tension wood pulp of *Populus* "*Tristis* #1" is definitely inferior in strength to that of normal wood, it actually compares quite favorably after some refining with that obtained from conventional pulps of other young or mature hardwoods (e.g., Barker 1974). Consequently, we believe that even with a high percentage of tension wood in its fast-growth juvenile stems, this species and perhaps similar ones may still hold promise as a valuable source of future hardwood fiber.

References

Anderson, H. W., Zsuffa, L. 1975. Yield and wood quality of hybrid cottonwood grown in two-year rotation. Forest Res. Rept. No. 101. Maple, Ontario: Ont. Min. Nat. Resources, Div. Forests.

Barker, R. G. 1974. Papermaking properties of young hardwoods. Tappi **57**(8):107-111.

Berlyn, G. P. 1961. Factors affecting the incidence of reaction tissue in *Populus deltoides* Bartr. Iowa State J. Sci. **35**(3):367-424.

Borchardt, L. G., Piper, C. V. 1970. A gas chromatographic method for carbohydrates as alditol-acetates. Tappi **55**(2):257-260.

Clermont, L., Bender, F. 1958. The chemical composition and pulping characteristics of normal and tension wood of aspen poplar and white elm. Pulp Paper Mag. Can. 59:139-143.

Correns, E. 1961. On abnormal wood fibers. Paperi ja Puu 43(2): 47-62.

Côté, W. A., Day, A. C., Timell, T. E. 1969. A contribution to the ultrastructure of tension wood fibers. Wood Sci. Technol. 3: 257-271.

Cram, W. H. 1960. Performance of 17 poplar clones in south central Saskatchewan. For. Chron. 36(3):204-208.

Crist, J. B., Dawson, D. H. 1975. Anatomy and dry weight yields of two Populus clones grown under intensive culture. USDA For. Ser. Res. Paper, NC-113. North Central For. Exp. Stn., St. Paul, MN.

Dadswell, H. E., Wardrop, A. B., Watson, A. J. 1958. The morphology, chemistry and pulping characteristics of reaction wood. In: Bolam, F. (Ed.): Fundamentals of papermaking fibers. London: Technical Section BPPMA, 187-219.

Dawson, D. H., Hutchinson, J. 1972. Research tackles pulpwood generation gap through maximum fiber yield program. For. Indust. 26/27: 17-18.

Dinwoodie, J. M. 1968. Failure in timber. Part I. Microscopic changes in cell-wall structure associated with compressive failure. J. Inst. Wood Sci. 4(3):37-53.

Einspahr, D. W. 1976. The influence of short-rotation forestry on pulp and paper quality. I. Short-rotation conifers. II. Short-rotation hardwoods. Tappi (in press).

Gardner, H. S., Einspahr, D. W. 1964. Reproducibility of micropulping wood samples. Tappi 47(7):432-434.

Hughes, F. E. 1965. Tension wood. A review of literature. For. Abstr. 26:2-9, 179-186.

Ilvessalo-Pfaffli, M. S., Alfthan, G. V. 1957. The measurement of fiber length with a semiautomatic recorder. Paperi ja Puu 39(11):509-516.

Isebrands, J. G., Bensend, D. W. 1972. Incidence and structure of gelatinous fibers within rapid-growing eastern cottonwood. Wood Fiber 4(2):61-71.

Isebrands, J. G., Parham, R. A. 1974. Tension wood anatomy of short-rotation Populus spp. before and after kraft pulping. Wood Sci. 6(3):256-265.

Jayme, G. 1951. The significance of tension wood content in poplar wood. Holz Roh-Werkstoff 9(5):173-175.

Jayme, G., Harders-Steinhauser, M., Mohrberg, W. 1951. The influence of percentage of tension wood upon the technological and chemical suitability of poplar woods. Papier 5:411-417, 445-447, 504-507.

Kaeiser, M. 1955. Frequency and distribution of gelatinous fibers in eastern cottonwood. Amer. J. Bot. 42(3):331-336.

Kearp, J. L. 1975. Projection of world demand and supply for wood fiber to the year 2000. Tappi 58(11):90-95.

Klauditz, W. 1962. The cellulose content of the wood of hybrid poplars in relation to pulp and paper manufacture. Papier 16:463-477.

Krempl, H. 1975. Differences in tension wood content in various poplar species. Holzforsch. Holzverwert. 27(6):131-136.

Obermans, H. E. 1936. A study of the effect of hemicelluloses on the beating and strength of pulps. Paper Trade J., Tappi Sect. 103 (7):83-91.

Parham, R. A. 1975. Critical-point drying for fiber microscopy. Tappi 58(3):138-140.

Ribe, J. H. 1974. Will short-rotation forestry supply future pulpwood needs? Pulp Paper 48(12):72-75.

Schroeder, H. A. 1976. Chemical pulp from hardwoods native to the South — Review of techniques, properties, and markets. Forest Prod. J. 26 (1):34-39.

Scurfield, G. 1973. Reaction wood: Its structure and function. Science 179(4074):647-655.

Thode, E., Peckham, J., Daleski, B. 1961. An evaluation of certain laboratory pulping methods. Tappi 44(2):81-88.

Timell, T. E. 1969. The chemical composition of tension wood. Svensk Papperstidn. 72(6):173-181.

Wardrop, A. B. 1963. Morphological factors involved in the pulping and beating of wood fibers. Svensk Papperstidn. 66(7):231-247.

Watson, A. J. 1956. Pulping characteristics of eucalypt tension wood. Proc. APPITA 10:43-59.

Watson, A. J., Dadswell, H. E. 1962. Influence of fiber morphology on paper properties. Part II. Early wood and late wood. APPITA 15 (6):116-128.

White, D. J. B., Robards, A. W. 1965. Gelatinous fibers in ash (*Fraxinus excelsior* L.). Nature 205:818.

Russell A. Parham
Kim W. Robinson
The Institute of Paper Chemistry
P. O. Box 1039
Appleton, WI 54911 U.S.A.

Jud G. Isebrands
USDA Forest Service
Institute of Forest Genetics
P. O. Box 898
Rhinelander, WI 54501 U.S.A.

Reproduction of Figures in Journal

Fig. 1. Please reproduce at 1:1.

2. Reduce to 2-column width.

3. Same.

4. Same.

5. Same.

6. Please reproduce at 1:1.

7. Reduce to 2-column width.

8. Reduce to 1-column width.

9. Same.

Figure Captions

Fig. 1. Typical cross-sectional views of unbeaten handsheets from normal wood (A) and tension wood (B). Average basis weights for these papers were 60.9 and 62.8 g/m^2, respectively. (Fig. 1-6 are scanning electron micrographs.)

Fig. 2. Higher magnifications of pulp fibers in unbeaten tension wood papers. Even thin-walled gelatinous (G) fibrs resist collapse (A). Note the apparently brittle nature of a fractured G-layer in B; this fiber also exhibits a series of surface dislocations.

Fig. 3. Typical cross-sectional views of handsheets from pulps beaten 45 min. Normal wood pulp (A) formed a very well consolidated sheet while tension wood (B) still produced a rather porous structure.

Fig. 4. Surface views of paper made from unbeaten pulps of normal wood (A) and tension wood (B). Note the well collapsed fibers in A versus the more rodlike fibers of tension wood, which form a bulky, open sheet.

Fig. 5. Handsheets from the same pulps as in Fig. 4 except after 45 min of beating. Interfiber bonding is well developed in the normal wood paper (A), but tension wood fibers appear relatively unscathed and still form an open sheet (B).

Fig. 6. Typical failure zones in 45-min-beaten handsheets resulting from tests in zero-span tensile. Fiber fracture characterized the well bonded normal wood paper (A), but tension wood paper (B) failed largely as a consequence of fiber pull-out.

Fig. 7. Physical properties of normal wood (NW) and tension wood (TW) handsheets as a function of beating time.

Fig. 8. Response of normal wood (NW) and tension wood (TW) pulp freeness to beating time.

Fig. 9. Relationship of normal wood (NW) and tension wood (TW) handsheet density to pulp freeness.

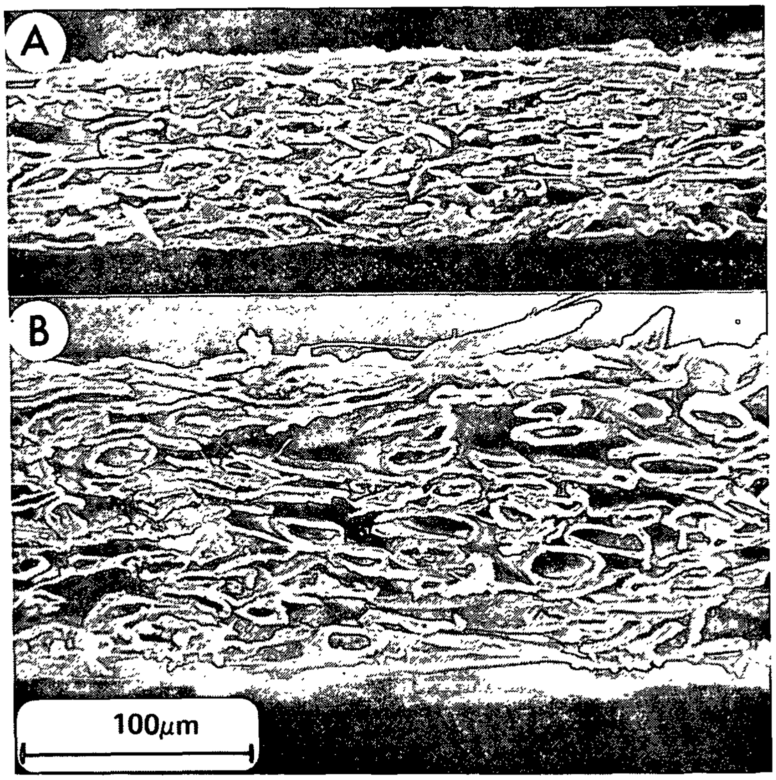

Figure 1

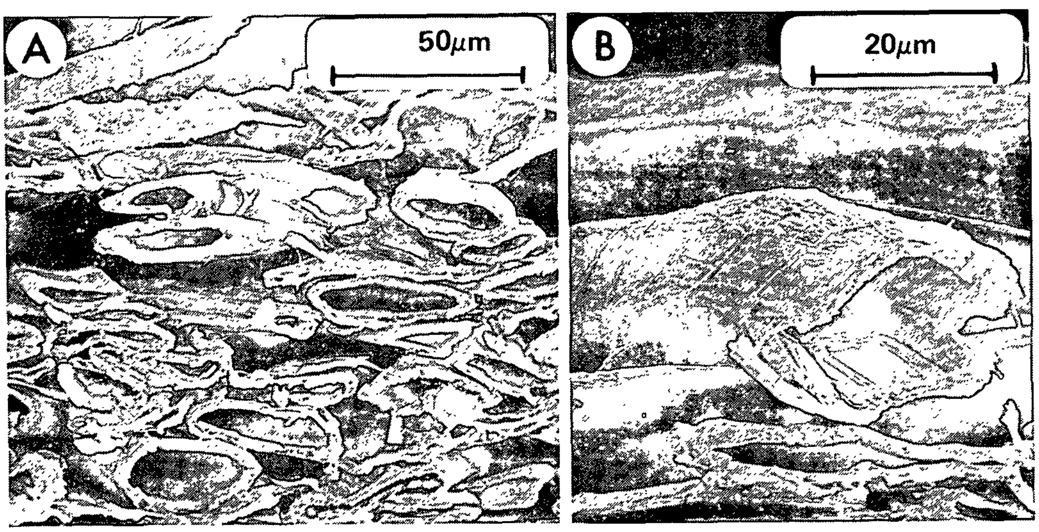

Figure 2

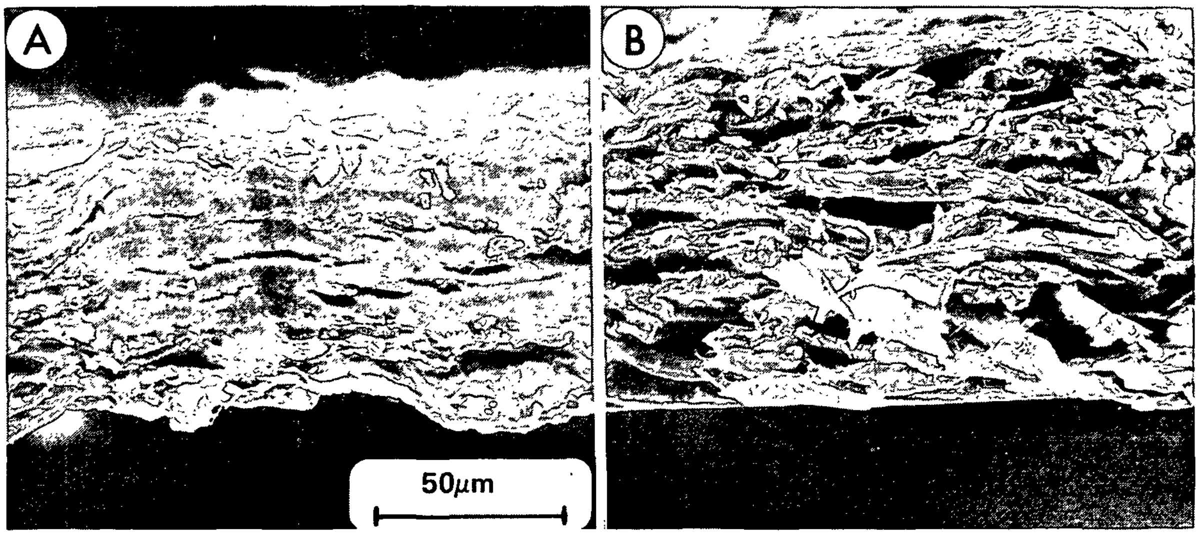

Figure 3

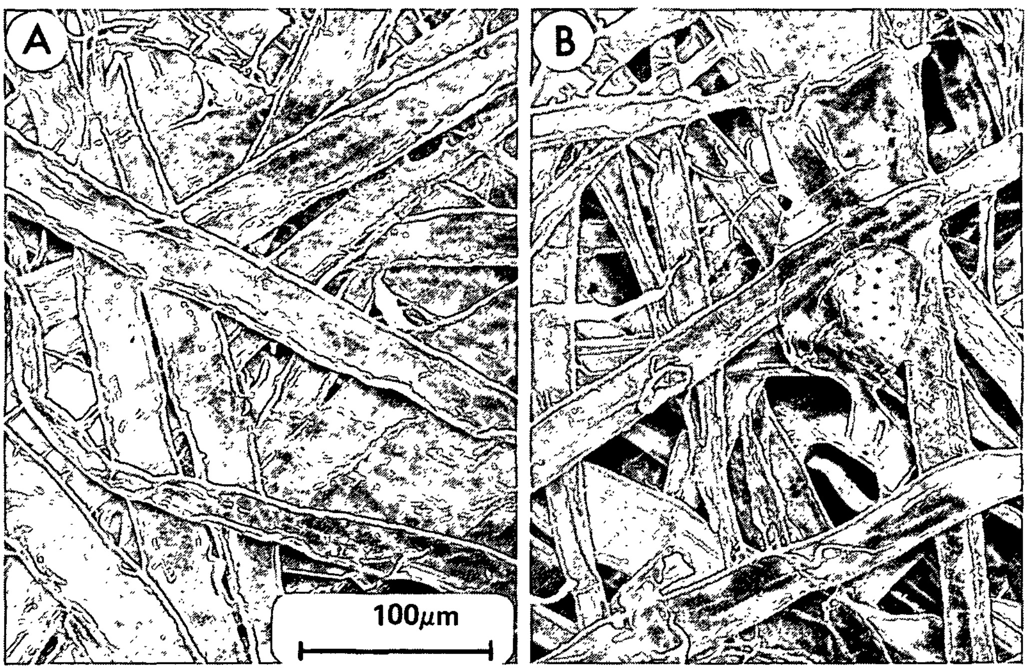

Figure 4

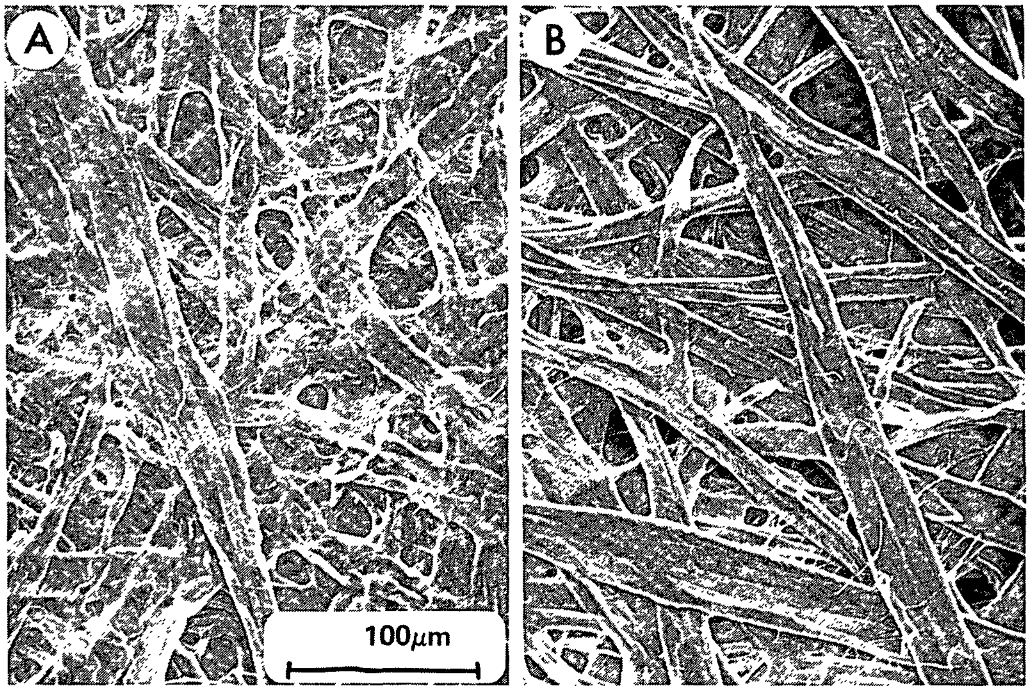

Figure 5

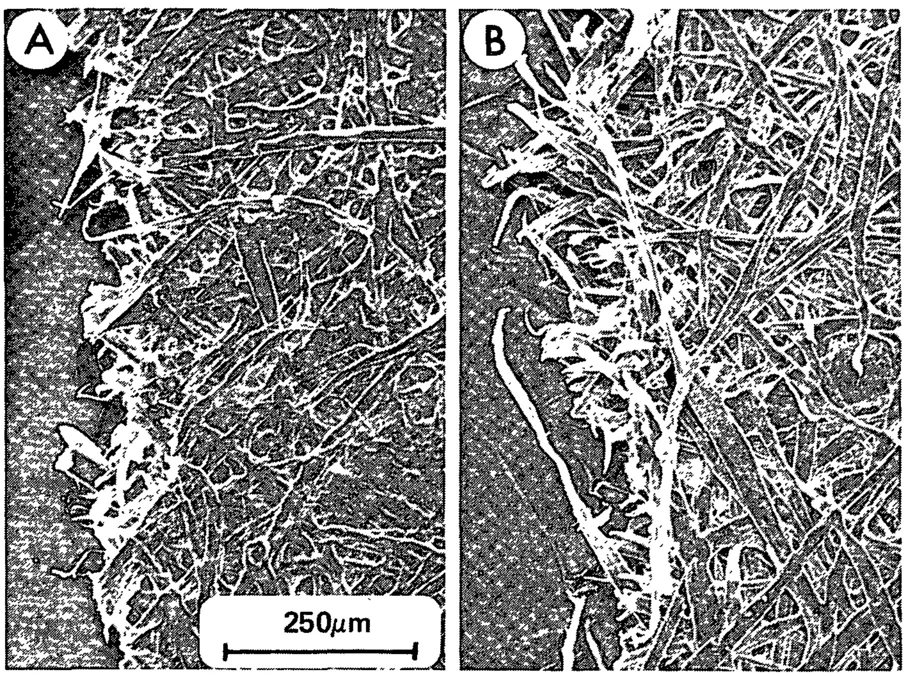

Figure 6

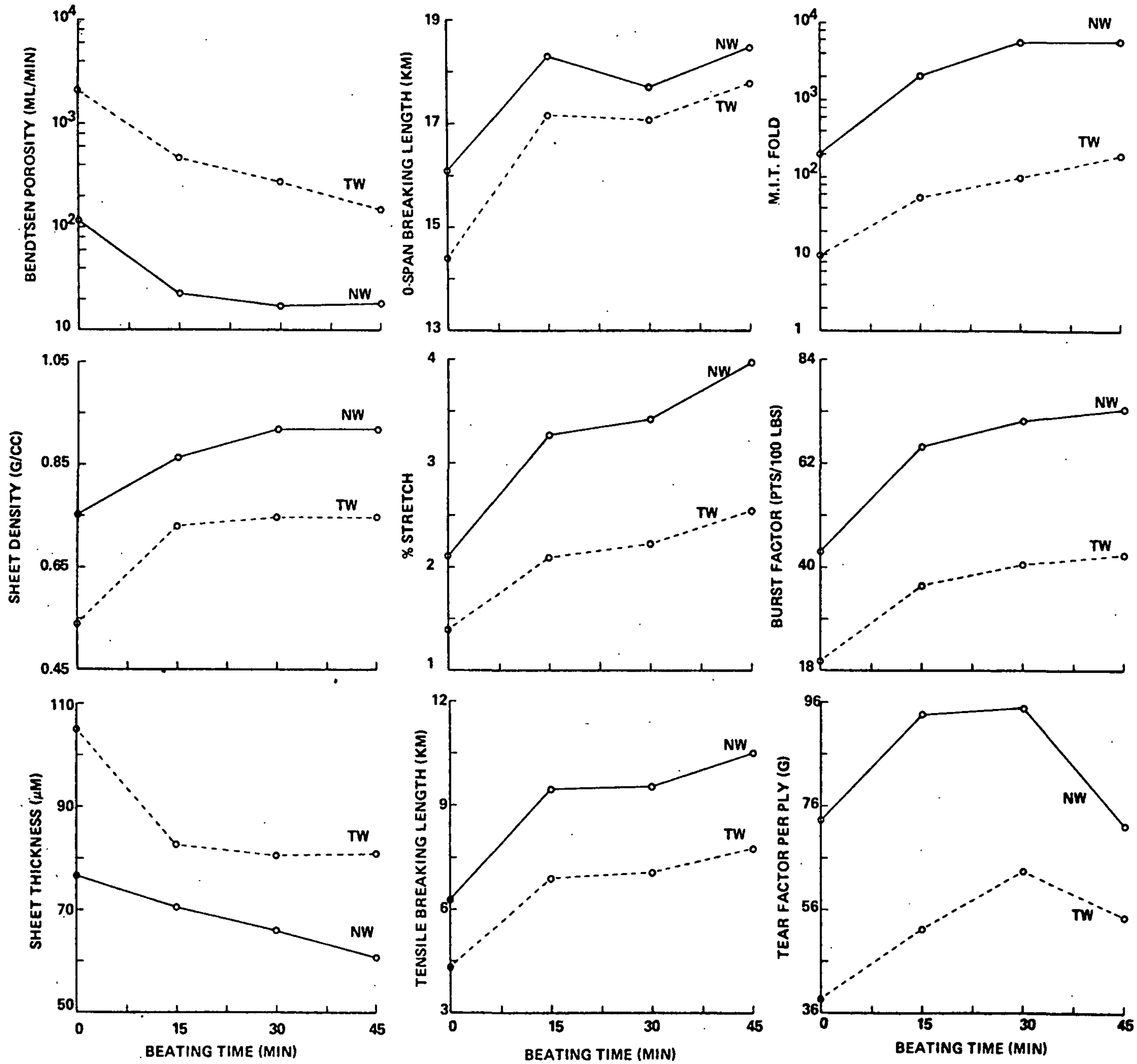
BENDTSEN POROSITY (ML/MIN)
10^4
10^3
10^2
10
TW
NW
0-SPAN BREAKING LENGTH (KM)
19
17
15
13
NW
TW
M.I.T. FOLD
10^4
10^3
10^2
10
1
NW
TW
SHEET DENSITY (G/CC)
1.05
0.85
0.65
0.45
NW
TW
% STRETCH
4
3
2
1
NW
TW
BURST FACTOR (PTS/100 LBS)
84
62
40
18
NW
TW
SHEET THICKNESS (μM)
110
90
70
50
TW
NW
TENSILE BREAKING LENGTH (KM)
12
9
6
3
NW
TW
TEAR FACTOR PER PLY (G)
96
76
56
36
NW
TW
0
15
30
45
BEATING TIME (MIN)

Figure 7

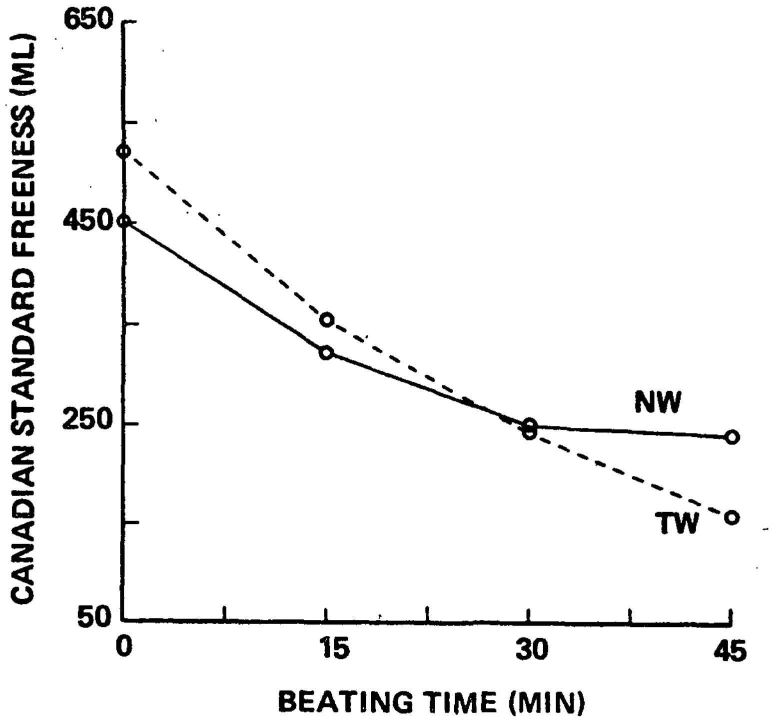

Figure 8

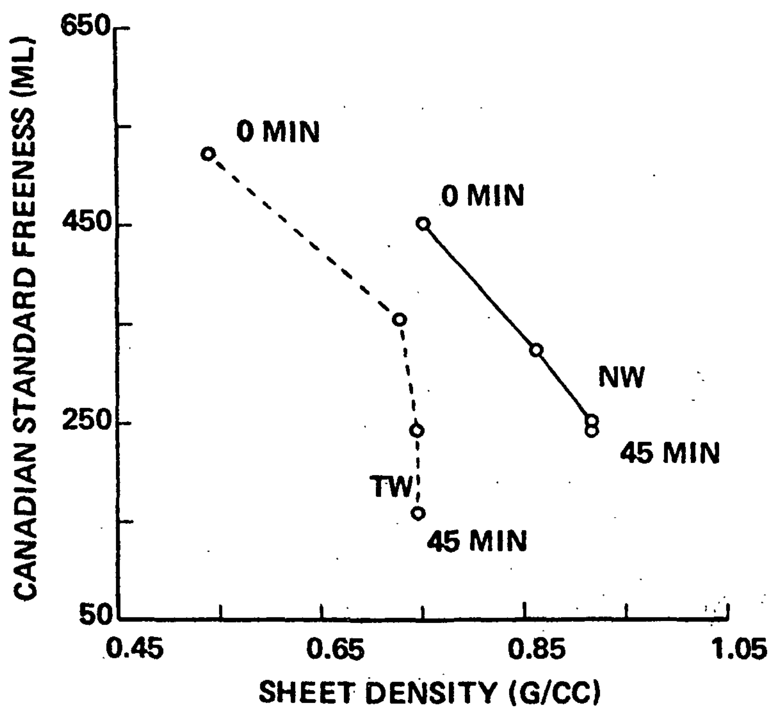

Figure 9